

Combinatorial Systems Evolution: Example of Standard for Multimedia Information

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Abstract. The article addresses the issues of combinatorial evolution of standards in transmission of multimedia information including the following: (a) brief descriptions of basic combinatorial models as multicriteria ranking, knapsack-like problems, clustering, combinatorial synthesis, multistage design, (b) a description of standard series (MPEG) for video information processing and a structural (combinatorial) description of system changes for the standards, (c) a set of system change operations (including multi-attribute description of the operations and binary relations over the operations), (d) combinatorial models for the system changes, and (e) a multistage combinatorial scheme (heuristic) for the analysis of the system changes. Expert experience is used. Numerical examples illustrate the suggested problems, models, and procedures.

Keywords: system evolution, multimedia information, standard, technological trajectories, combinatorial optimization, heuristics, decision making, expert judgment.

1. Introduction

In recent years the significance of the evolution or development of engineering systems is increasing (Conradi and Westfetchedel, 1998; Lehman and Ramil, 2001; Levin, 2006, 2007a; Otto and Wood, 1998; Sahal, 1981; Taura and Kubota, 1999). In the main, these studies involve the following directions: (1) basic engineering systems (e.g., transport systems; Sahal, 1981); (2) software systems (Conradi and Westfetchedel, 1998; Lehman and Ramil, 2001); (3) hardware systems (e.g., VLSI; Katz, 1990) and (4) special engineering history bases (Taura and Kubota, 1999). Usually, tree-like models (e.g., *AND-OR tree*) are used for modeling the systems and their development/evolution processes (Conradi and Westfetchedel, 1998; Katz, 1990; Levin, 2006). An approach to combinatorial evolution of modular systems, suggested by M.Sh. Levin, is described in the following sources: (i) evolution of DSS COMBI-PC (Levin, 1998); (ii) evolution of devices for

signal processing (Levin, 2006); (iii) evolution of requirements to topology of communication networks (Levin, 2007a); (iv) analysis of system changes for a building (Levin and Danieli, 2005; Levin, 2006); and (v) general description (Levin, 2006). Generally, it is possible to examine the following three layers (Levin, 2006): (i) products/systems; (ii) requirements to the products/systems; and (iii) standards for the products/systems.

Our discussion article addresses the issues of combinatorial evolution of standards for multimedia information (Bhaskaran and Konstantinidis, 1995; Chiariglione, 1995, 1997; Fomin, 2001; Ghanbari, 1999; Hoang and Vitter, 2002; Jain, 1989; Koenen, 2001; Kuhn, 1999; Le Gall, 1991; Pereira, 2002; Schafer and Sikora, 1995; Sun and Reibman, 2001): (a) a structural description of standard series MPEG (Chiariglione, 1995; Chiariglione, 1997; Fogg *et al.*, 2002; Le Gall, 1991; Mitchell *et al.*, 1996; Watkinson, 2001) and a structural description of system changes for the standards, (b) a set of system changes operations (including multi-attribute description of the operations and some binary relations over the operations), (c) combinatorial models for the changes, and (d) multistage 'technological' trajectories (Levin, 2006, 2007a).

Basic combinatorial models (multicriteria ranking, knapsack-like problems, clustering, combinatorial synthesis, and multistage design) are briefly described. In the article two kinds of models are used: (i) a tree-like system model (*AND-OR tree*) for the description of standards and (ii) combinatorial models for modeling the changes of standards (e.g., multicriteria ranking, knapsack-like models). A multistage combinatorial scheme (heuristic) and expert judgment are used for the evaluation of the system changes. Numerical examples illustrate the problems, models, and procedures.

2. Underlying Combinatorial Problems

The problem of multicriteria ranking of alternatives is basic one in multiple criteria decision making (Forgionne, 1991; Simon *et al.*, 1987). The problem is targeted to dividing an initial set of multi-attribute alternatives into linear ordered (by a total quality) subsets. Many well-known techniques can be used for multicriteria ranking problem, for example, (1) multi-attribute utility analysis (e.g., Fishburn, 1970; Keeny and Raiffa, 1976); (2) Pareto approach (Pareto, 1971); (3) interactive methods (e.g., Koksalan *et al.*, 1984); (4) Analytic Hierarchy Process (AHP; Saaty, 1988); (5) outranking techniques (e.g., Roy, 1996; Vincke, 1992); (6) special knowledge bases and neural networks (e.g., Wang and Malakooti, 1992), etc. In our research, multicriteria ranking procedures based on Pareto approach and outranking technique are used.

Knapsack problem is targeted to selection of items while taking into account their *utility* and some resource constraints. The problem is NP-hard (Garey and Johnson, 1979; Kellerer *et al.*, 2004; Martello and Toth, 1990; Sinha and Zolters, 1979) and may be solved by enumerative methods (e.g., Branch-and-Bound, dynamic programming), approximate schemes with a limited relative error, and heuristics (e.g., Martello and Toth, 1990). Here a simple procedure (based on algorithm by Dantzig) is used. In the case of a multiple choice problem, the units (e.g., items) are divided into groups and items

from each group are selected while taking into account a total resource constraint. Solving methods for knapsack problem are used for multiple choice problem. Here a simple heuristic (an analogue of algorithm by Dantzig) is used as well.

Clustering problem is a basic scientific problem in many domains (Agrawal and Procopiuc, 2001; Anderberg, 1973; Jain *et al.*, 1999; Johnson, 1967; Levin, 2007b; Mirkin, 2005; Serban and Campan, 2008):

Divide an initial set of elements into clusters (subsets, groups) to minimize the 'distances' (or proximities) between elements in the same clusters (i.e., 'intracluster distances').

The following data can be used as input: (a) parameters of each element and/or (b) proximity ('distance') between elements. The problem is close to the above-mentioned multicriteria ranking but without the order over the set of obtained subsets. In network design and management, clustering is used to get local subsystems (e.g., areas). Basic clustering algorithms (agglomerative algorithm, etc.) are described in Agrawal and Procopiuc (2001), Anderberg (1973), Hartigan (1975), Jain *et al.* (1999), Johnson (1967), Levin (2007b), Mirkin (2005), Serban and Campan (2008). Often polynomial heuristics are used (e.g., agglomerative algorithm). Here an agglomerative algorithm was used (Levin, 2007b; Serban and Campan, 2008).

Combinatorial morphological synthesis is based on Hierarchical Morphological Multicriteria Design (HMMD) and generalizes multiple choice problem (Levin, 1998, 2005, 2006). HMMD extends well-known morphological analysis (Jones, 1981; Zwicky, 1969) by the use of ordinal quality estimates for design alternatives and their compatibility. A brief description of HMMD is as follows (Levin, 1998, 2005, 2006, 2007a; Levin and Danieli, 2005). The examined composite (modular, decomposable) system consists of components and their interconnection (IC) or compatibility. Basic assumptions of HMMD are the following: (a) a tree-like structure of the system; (b) a composite estimate for system quality that integrates components (subsystems, parts) qualities and qualities of IC (compatibility) across subsystems; (c) monotonic criteria for the system and its components; and (d) quality of system components and IC are evaluated on the basis of coordinated ordinal scales. The designations are: (1) design alternatives (DAs) for leaf nodes of the model; (2) priorities of DAs ($r = \overline{1, k}$; 1 corresponds to the best one); (3) ordinal compatibility (IC) for each pair of DAs ($w = \overline{0, l}$; l corresponds to the best one).

The basic phases of HMMD are: (1) design of the tree-like system model; (2) generation of DAs for leaf nodes of the model; (3) hierarchical selection and composing of DAs into composite DAs for the corresponding higher level of the system hierarchy; and (4) analysis and improvement of composite DAs (decisions).

Let S be a system consisting of m parts (components): $P(1), \dots, P(i), \dots, P(m)$. A set of design alternatives is generated for each system part above. The problem is:

Find a composite design alternative $S = S(1) \star \dots \star S(i) \star \dots \star S(m)$ of DAs (one representative design alternative $S(i)$ for each system component/part $P(i)$ ($i = \overline{1, m}$) with non-zero IC between design alternatives.

A discrete space of the system excellence on the basis of the following vector is used: $N(S) = (w(S); n(S))$, where $w(S)$ is the minimum of pairwise compatibility between

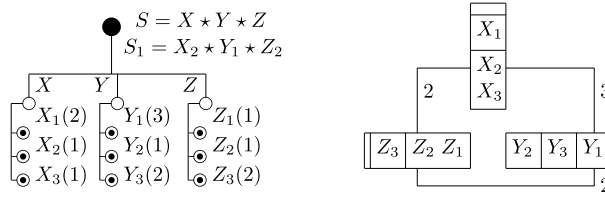


Fig. 1. Example of composition (priorities are shown in parentheses).

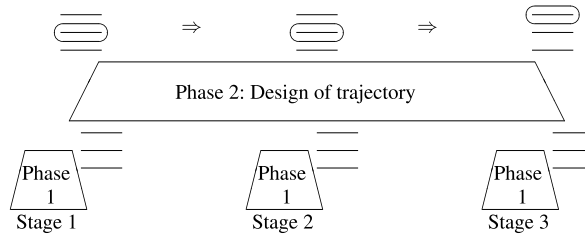


Fig. 2. Multistage design.

DAs which correspond to different system components (i.e., $\forall P_{j_1}$ and P_{j_2} , $j_1 = \overline{1, m}$, $j_2 = \overline{1, m}$, $j_1 \neq j_2$) in S , $n(S) = (n_1, \dots, n_r, \dots, n_k)$, where n_r is the number of DAs of the r th quality in S . As a result, we search for composite decisions which are nondominated by $N(S)$. Thus, the following layers of system excellence can be considered: (i) ideal point; (ii) Pareto-effective points; (iii) a neighborhood of Pareto-effective DAs (e.g., a composite decision of this set can be transformed into a Pareto-effective point on the basis of an improvement action(s)). Clearly, the compatibility component of vector $N(S)$ can be considered on the basis of a poset-like scale too (as $n(S)$). In this case, the discrete space of system excellence will be an analogical lattice. Fig. 1 illustrates the composition problem. In the example, composite DA is: $S_1 = X_2 * Y_1 * Z_2$, $N(S_1) = (2; 2, 0, 1)$.

Multistage design or design of system trajectory is described in Levin (1998, 2006). In this case the following solving scheme is used (Fig. 2):

Phase 1. System design for each time stage (HMMD) to get a set of stage decisions.

Phase 2. Design of a system trajectory as a combination of results obtained at the previous phase. Here HMMD is used as well.

3. Standard

Fig. 3 depicts a scheme for information processing: a corresponds to video signal, b corresponds to audio signal, c corresponds to synchronization signal, and d corresponds to test signal. This scheme is the basic object for standardization processes. The *receiver* part has the *inverse* (for decoding/decompression) structure.

An analysis of the requirements to information processing can be based on the following technological schemes: (1) *input data* (audio, video, text synchronization data,

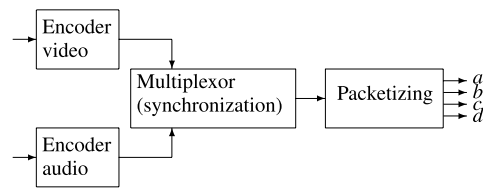


Fig. 3. Scheme of information processing.

synthetic information); (2) *processing* (coding, network transmission, decoding); and (3) *output data* (for an user system: a human, an applied system). Thus, requirements can be considered while taking into account the following: (1) object (i.e., data of certain kind, a process); (2) a basic point for the analysis (i.e., a stage of the above-mentioned cycle of information processing: input part, output part, intermediate technological part). In addition, it is reasonable to point out a classification of data as follows: (i) kind (analog, digital); (ii) time mode (real time, non-real time). Generally, the following two kinds of requirements have to be examined: (1) quality of a result (i.e., resultant information), (2) expenditure (cost, time estimates, etc.).

Quality of the resultant pictures can be based on the following: PSNR, delay, errors, latency, loss (e.g., packets loss, frame loss). From the viewpoint of the standard changes we will consider change operations and the requirements to the operations as follows:

I. Profit of operations: quality of output, level of requirements to input, and level of requirements to technological stages (e.g., coding, network transmission, decoding).

II. Cost of the operations: required additional R & D, required additional software development, required additional design of hardware, complexity of an additional manufacturing stage, and simpleness of implementation into existing technologies.

Further, it may be useful to examine a macro-evolution process for standard systems. The line of standards MPEG is examined (Chiarioglone, 1997; Fogg *et al.*, 2002; Le Gall, 1991; Mitchell, 1996; Watkinson, 2001). The main chain of the system evolution consists in the following (Fig. 4):

JPEG \Rightarrow MPEG-1 \Rightarrow MPEG-2 \Rightarrow MPEG-4.

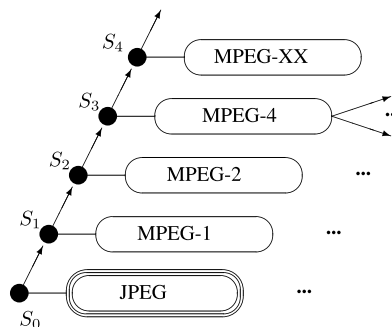


Fig. 4. Macro-evolution process.

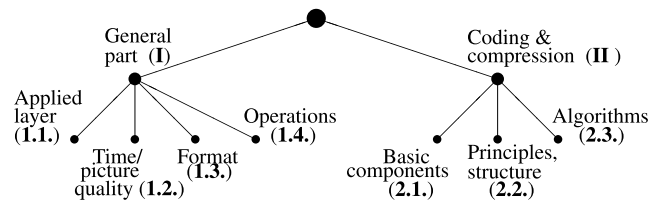


Fig. 5. Generalized structure of standard.

Table 1
Structure of standard

Items	Content
I.	General part
1.1.	<i>Applied layer</i> (videotelephony, videoconferencing, digital broadcast, digital storage media, cable and satellite TV, video service over network, DVD, camcorder, personal streaming, etc.)
1.2.	<i>Time and picture quality mode</i>
1.2.1.	<i>Time mode</i> (delay: 0.15 s for 'face-to-face' (F2F), 1.0 s for 'interactive')
1.2.2.	<i>Picture quality</i> (good picture quality, low picture quality)
1.3.	<i>Format</i>
1.3.1.	<i>Resolution</i>
1.3.2.	<i>Color decomposition</i> (luminance, chrominance)
1.4.	<i>Basic operations</i>
1.4.1.	<i>Transformation</i>
1.4.2.	<i>Playback/features</i>
1.4.3.	<i>Streaming</i> (video, audio, synchronization, streaming data, testing, control)
II.	Coding/compression
2.1.	<i>Basic components</i>
2.1.1.	<i>Video coding</i> (methods for transformation into digital codes)
2.1.2.	<i>Motion estimation</i> (vector, etc.)
2.1.3.	<i>Coding structure</i> (group of pictures GOP)
2.2.	<i>Principles and structure</i>
2.2.1.	<i>Principles</i>
2.2.1.1.	<i>Block decomposition</i>
2.2.1.2.	<i>Scanning</i>
2.2.2.	<i>Structure</i> (basic processing scheme, extended processing scheme, 'open structure' including transcoding)
2.3.	<i>Algorithms</i>

Here a structural description of standards for video information processing is considered as the following set of basic properties, which are organized by a tree (Fig. 5, Table 1). In the main, algorithms are not examined in this article.

The described generalized structure of standards (Fig. 5, Table 1) is used as a basis to examine the MPEG standards. Descriptions of MPEG-1, MPEG-2, and MPEG-4 are presented in Table 2.

Table 2
Description of MPEG-1, MPEG-2, MPEG-4

Items	MPEG-1	MPEG-2	MPEG-4
1.1	Bit rate: 64 kbit/s – 2 Mbit/s, digital media storage, computer & telecommunication networks	Bit rate: 4–80 Mbit/s, digital broadcast TV, high quality storage media, cable satellite TV, video service over the networks	Bit rate: 24–1024 kbit/s, digital cable, camcorder, WEB, security for applications, interactive mode
1.2.1	Delay	Real time, low delay 500–700 ms, delay between audio and video ≈ 300 ms	Delay 500–700 ms
1.2.2	No error, low picture quality	Good picture quality by the following basic modes: error detection, resynchronization, and data recovery	Variable (used independent)
1.3.1	Low resolutions (CIF, QCIF)	CIF, QCIF, full D1, Half D1, HDTV, high resolution (NTSC, PAL)	From sub-QCIF to 'Studio'
1.3.2	(Sampling) 4 : 2 : 0	(Sampling) 4 : 2 : 0, 4 : 2 : 2, 4 : 4 : 4 (high profile)	(Sampling) 4 : 2 : 0, 4 : 2 : 2, 4 : 4 : 4
1.4.1	Audio transformation, moving picture information, combination of audio/visual information (system level)	(1) Coding: audio transformation, moving picture information, combination of audio/visual information; (2) Dolby Digital, DVD 16 × 9 (TV) and scalability as follows: SNR (quality), spatial, temporal	
1.4.2	Random access, fast forward/reverse search, reverse playback, audio/visual synchronization, good error behavior, delay, editing, format, rate control	Random access, fast forward/reverse search, reverse playback, audio/visual synchronization, good error behavior, delay, editing, format, rate control, scalability	As in MPEG-2
1.4.3	Video, audio, synchronization, system stream, and program stream	Video, audio, systems, synchronization, testing, digital storage media control, real time interface, and transport stream	Streaming data (media objects), real-time streams, position of resynchronization marker is anywhere (delay between audio and video is ≈ 300 ms)
2.1.1	Some transform coding: variable word length coding of coefficient structure	New VLC tables for DCT (non-linear), frame/field compensation	Usage of VLC tables for error detection, coding of natural/synthetic data, high flexibility of coding for audio/video
2.1.2	–1024 to 1023 pixel (for half), –512 to 511.5 pixel (for full pixel)	(a) –2048 to 2047.5 pixel (for half), –1022 to 1023 pixel (for full pixel), (b) frame/field motion vector	
2.1.3	As in MPEG-2	Intra frame: <i>I</i> (intrapicture coded), inter frames: <i>P</i> (coded using motion compensation prediction), <i>B</i> (coded from <i>I</i> , <i>P</i>), <i>D</i> (for location purpose in fast search)	
2.2.1.1	16 × 16 (macroblock), 8 × 8 (block)	8 × 8	Object-based (VOB)
2.2.1.2	Progressive scan (zigzag)	Progressive scan (zigzag)/interlaced (alternative)	
2.2.2	Pre-processing, encoding, improvement of post-processing	Pre-processing, encoding, improvement of post-processing	Separation of motion and texture data, prioritized transmission of each coded frame

The following abbreviations are used hereinafter: CIF (Common Intermediate Format), QCIF (Quarter CIF), HDTV (High Definition Television), NTSC or standard of NTSC (National Television Standards Committee), PAL (Phase Alternation by Line, TV standard PAL), Dolby Digital (format Dolby Digital), DVD (Digital Versatile Disk), SNR (Signal to Noise Ratio), VLC (Variable-Length Coding), DCT (Discrete Cosine Transform), VBR (Variable Bit Rate, a version of coding in MPEG-2), and CBR (Constant Bit Rate, a version of coding in MPEG-2).

4. Changes in Standard

Basic trends of multimedia standard development are as follows:

1. Extension of applications: (a) storage media; (b) broadcast, and (c) WEB applications. Concurrently, it is reasonable to point out the 2nd development line by time modes: off line mode, on-line (real time) mode, interactive mode.
2. Decreasing a delay.
3. Improvement of quality:
 - 3.1. Decreasing the errors.
 - 3.2. Improvement of resolution.
 - 3.3. Improvement of quality for synchronization.
4. Providing the additional applications: *search*, *archiving*, *indexing*, and *multimedia databases*.

Further, changes of the MPEG standards are described in Table 3. The revelation of the standard changes is based on comparing the standard parts/components. Figs. 6–10 illustrate the comparison process for some MPEG parts. Here two-stage evolution for some parts/components of MPEG standards is depicted: (a) for part 1.1 (Fig. 6), (b) for component 1.3.1 (Fig. 7), (c) for component 1.4.3 (Fig. 8), (d) for component 2.1.1 (Fig. 9), and (e) for component 2.1.3 (Fig. 10). In Fig. 10, *D* corresponds to ‘fast search’, *D'* corresponds to possible use in a modified mode (*D*-frame).

The improvement of communication technology is a significant part of changes in transmission of multimedia information. It is reasonable to point out the following basic contemporary problems of communication technology (Chiariglione, 1997; Sun and Reibman, 2001; Watkinson, 2001): (1) full integration of various networks (wireless, satellite network, broadcast, Internet, etc.); (2) quality of service (QoS) (e.g., delay, delay jitter, packet loss, bit-error rate, burst-error rate, and burst-error length); (3) CBR or VBR; (4) synchronization of video, audio, data, etc.; (5) circuit-switching or packet-switching; and (6) multiplexing.

There exist two kinds of change actions as follows:

I. Global changes: new networks, new communication equipment (new generation of communication satellite, laser-based communication, etc.).

II. Local changes: (a) usage of VBR for CBR networks, (b) effective buffering, (c) smoothing (e.g., statistical multiplexing).

Evidently, local improvements can provide essential increasing of effectiveness for existing communication networks (e.g., quality of service).

Table 3
Changes

Items	Between MPEG-2 and MPEG-1	Between MPEG-4 and MPEG-2
1.1.	Digital broadcast TV, high quality video/audio storage, cable satellite TV, video service, high quality audio transmission, and bit rate (MP3, stereo, etc.): 4–80 Mbit/s	DVD, camcorder, WEB (personal streaming), 24–1024 kbit/s (by compression: 1000 times)
1.2.1.	(i) Low delay (from 0.15 to less than 0.15 for F2F), (ii) real-time delay (1–0.4 s)	(a) Delay (from 500–700 ms), (b) delay between audio and video \approx 300 ms
1.2.2.	(a) Good picture quality, (b) specific error resilience modes	Use of VLC tables for error detection (possible)
1.3.1.	Full D1, Half D1, HDTV	From QCIF to ‘Studio’ file format
1.3.2.	(Sampling) 4 : 2 : 2	4 : 4 : 4
1.4.1.	Scalability (2/3 layers)	Object-based scalability
1.4.2.	Upward/downward	Pause, slow
1.4.3.	(1) Testing, (2) digital storage media control, (3) software simulation, (4) real-time interface, (5) transport stream, and (6) 10 bit video (Studio quality)	(a) Streaming data, multiplex and synchronize the data associated with media objects, transport over IP, (b) flexibility to position markers anywhere in a frame
2.1.1.	(a) Non-linear quantization table with increased accuracy for small values, (b) alternative scan for DCT coefficient, (c) MV: –2048–2047.5 pixel (for half), (d) new VLC tables for DCT coefficient coding, (e) frame/field scan for DCT and MV, and (f) no D-frames	
2.1.2.	Dual prime motion compensation (for <i>P</i> -frame)	Hybrid coding of natural (i.e., pixel-based) images with synthetic (computer generated) scenes
2.1.3.		Highly flexible way of object representation for video and audio data
2.2.		Separation of motion and texture
2.2.1.1.	Scale format: 1 × 1, 2 × 2, 4 × 4	
2.3.		Scenic material should be acceptable to the algorithms that may include special modes for head&shoulders scenes, graphics, tests, etc.

Now a basic set of change operations it is possible to describe:

Group 1. Extension of range for data types: storage (interface with applied systems): files, DVD, camcorder O_1 ; broadcast (coding/decoding): digital broadcast TV, cable-satellite, video-conferencing O_2 ; and network: video service over network, personal streaming, security for application, interactive mode O_3 .

Group 2. Change of resolution: design of new equipment for improvement of picture quality: O_4 for software, O_5 for hardware; change of existing equipment for improvement of picture quality: O_6 for software, O_7 for hardware; and change of existing communication technology for improvement of picture quality: O_8 for software, O_9 for hardware.

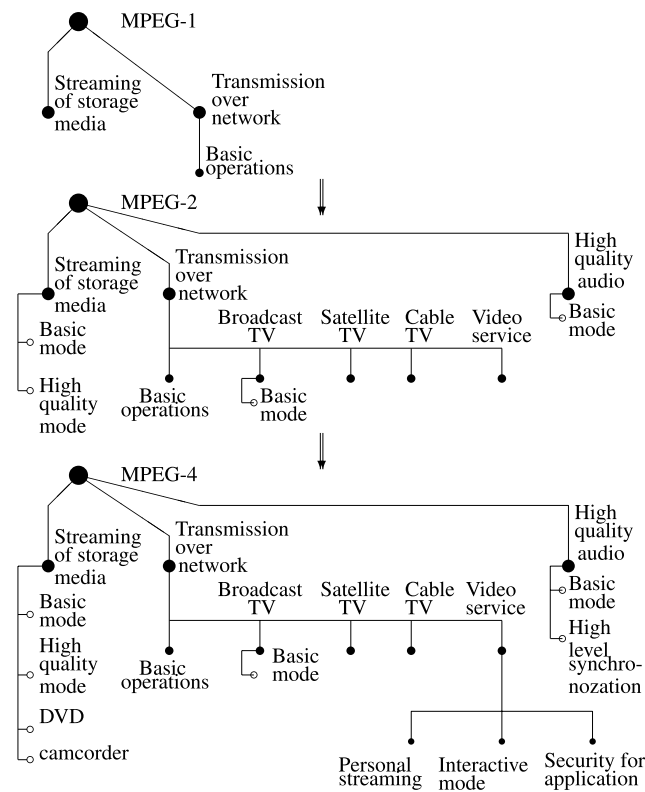


Fig. 6. Applied layer (1.1).

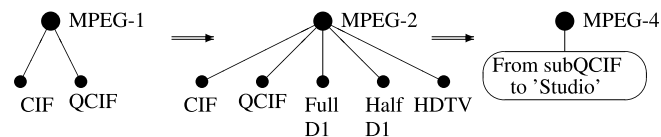


Fig. 7. Resolution (1.3.1).

Group 3. Change of time mode: decreasing a delay O_{10} and realization of real-time mode (conferencing, interactivity) O_{11} .

Group 4. Errors: decreasing of losses O_{12} and decreasing a latency O_{13} .

Group 5. Transmission: extension of service information (testing, control, etc.) O_{14} ; additional modes (real time, streaming data) O_{15} ; support of retrieval modes (e.g., by D-frames) O_{16} ; and support of retrieval modes increasing the group of pictures (from 2 frames to 7 frames) O_{17} .

Group 6. Object and scalability: implementation of object-based approach, i.e., semantic analysis of transmitted information (from frame to object/scene, synchronization markers for objects, global motion detection) O_{18} ; implementation of scalability O_{19} ; and variable blocking O_{20} .

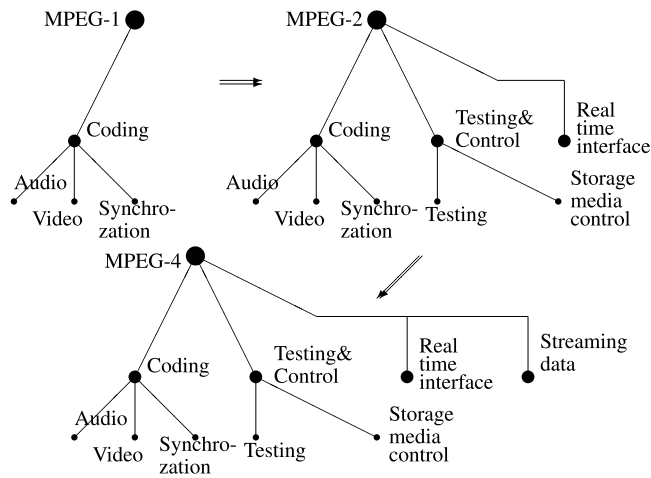


Fig. 8. Transport stream (1.4.3).

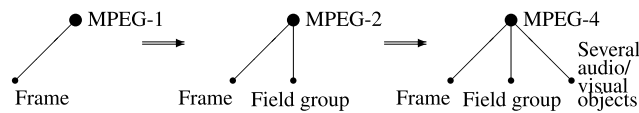


Fig. 9. Video coding (2.1.1).

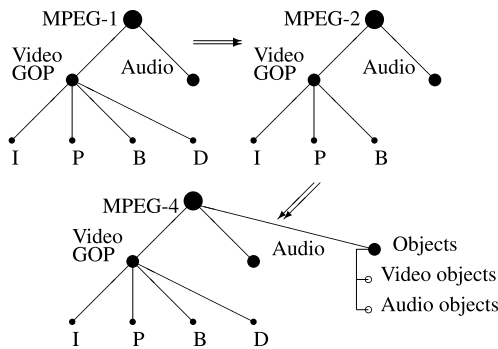


Fig. 10. Coding structure/group of pictures GOP (2.1.3).

Further, it is reasonable to examine the following three kinds of binary relations over the change operations set: (1) *equivalence* R^e ; (2) *complementarity (compatibility)* R^c (Table 4); (3) *condition for the operation* $R^f : \alpha \rightarrow \beta$, for example: $1 \rightarrow 6$, $1 \rightarrow 12$, $1 \rightarrow 14$, etc. In Table 4, the following designations are used: \star corresponds to object-based relation; \diamond corresponds to soft-hard relation; \triangle corresponds to service-mode relation; and \spadesuit corresponds to time-mode relation. For *equivalence* R^e the following operations pairs are examined: (O_4, O_5) , (O_6, O_7) , (O_8, O_9) , and (O_{18}, O_{20}) . Some structural descriptions of compatibility are shown in Figs. 11 and 12. These relations have to be used

Table 4
Binary relation compatibility R^c

	O_3	O_4	O_5	O_6	O_7	O_8	O_9	O_{10}	O_{11}	O_{12}	O_{13}	O_{14}	O_{15}	O_{16}	O_{18}	O_{19}	O_{20}
O_1																	
O_2																	
O_3								♠	♠			♠	♠	♠			
O_4		◇						*		*	*	*	*	*	*	*	*
O_5		◇						*		*	*	*	*	*		*	
O_6				◇													
O_7					◇												
O_8						◇											
O_9							◇										
O_{10}	♠	*	*						♠				♠				
O_{11}	♠							♠					♠				
O_{12}		*	*														
O_{13}		*	*														
O_{14}	♠	*	*											△			
O_{15}	♠	*	*					♠	♠								
O_{16}	♠	*	*										△				
O_{17}																	
O_{18}		*															*
O_{19}		*	*														
O_{20}		*													*		

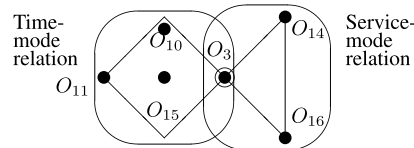


Fig. 11. Compatibility with basic node O_3 .

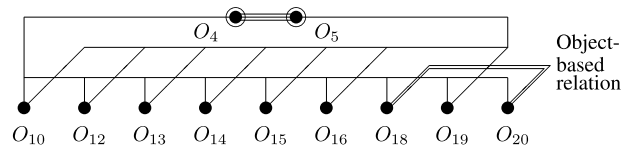


Fig. 12. Compatibility with basic nodes O_4 and O_5 .

as structural constraints. In addition, a time correspondence for each operation is evaluated as a time restriction (Table 5). The following three time stages are used: (a) Stage 1 (past) for some interpolation problems; (b) Stage 2 (near future) for short-term forecast (several years: 2–4); and (c) Stage 3 (future) for long-term forecast (5–10 years).

Table 5
Correspondence to a time stage

	1: Past	2: Near future	3: Future
O_1	*	*	*
O_2	*	*	*
O_3	*	*	*
O_4	*	*	*
O_5	*	*	*
O_6	*	*	*
O_7	*	*	*
O_8	*	*	*
O_9	*	–	*
O_{10}	*	*	–
O_{11}	*	*	–
O_{12}	*	*	*
O_{13}	*	*	*
O_{14}	–	*	*
O_{15}	*	*	–
O_{16}	–	–	*
O_{17}	–	*	*
O_{18}	–	*	*
O_{19}	–	*	*
O_{20}	–	*	*

Further, for an analysis of the above-mentioned change operations it is reasonable to consider two main their properties: (1) effectiveness (*profit*) and (2) required resources. As a result, a multicriteria description and components of the description can be used in optimization problems for the analysis of system changes. Here the following criteria for evaluation of change operations are used:

Group 1. Utility: quality of video C_1 ; quality of audio C_2 ; quality of synchronization C_3 ; quality of data C_4 ; and quality of retrieval C_5 .

Group 2. Technological environment: new technological opportunity C_6 .

Group 3. 'Cost': required additional R & D C_7 ; required new software C_8 ; required new hardware C_9 ; and volume of manufacturing C_{10} .

Importance weights of the criteria are presented in Table 6. Table 7 contains estimates of the change operations upon criteria and priorities (results of multicriteria ranking for three time stages accordingly; 1 corresponds to the best level).

5. Illustrative Numerical Examples

First, multicriteria ranking is considered. Table 7 contains the results of multicriteria ranking of the change operations (priorities) for three cases/stages above:

Table 6
Weights of criteria

	Stage 1	Stage 2	Stage 3
C_1	5	5	5
C_2	3	4	5
C_3	3	4	5
C_4	2	2	4
C_5	0	0	3
C_6	1	3	4
C_7	-1	-2	-4
C_8	-3	-4	-4
C_9	-4	-4	-4
C_{10}	-5	-5	-5

Table 7
Estimates on criteria and priorities

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	Priorities p_i		
O_1	5	5	5	5	5	5	5	3	4	5	2	2	1
O_2	5	5	5	5	-	4	5	4	4	5	2	2	2
O_3	-	-	-	5	5	5	5	5	1	2	2	2	2
O_4	4	4	4	4	5	5	5	5	2	3	2	2	2
O_5	4	4	4	4	2	4	5	4	5	4	2	2	2
O_6	3	3	3	2	0	2	3	4	0	1	1	2	2
O_7	3	3	3	0	0	2	3	2	4	3	2	2	2
O_8	5	5	5	5	5	5	5	5	0	4	1	1	1
O_9	5	5	5	5	5	5	5	2	5	5	2	1	1
O_{10}	3	3	5	3	1	4	5	4	3	2	2	2	2
O_{11}	-	-	-	-	3	5	4	4	5	5	3	3	3
O_{12}, O_{13}	5	5	5	4	1	2	5	5	1	2	1	2	2
O_{14}	3	3	5	5	5	5	5	5	3	3	2	2	2
O_{15}	-	-	-	5	5	5	5	5	1	3	3	3	2
O_{16}	-	-	-	-	5	5	5	4	-	-	3	3	3
O_{17}	5	-	-	-	3	4	3	5	3	4	2	2	2
O_{18}	5	2	4	4	5	5	5	5	2	3	2	2	2
O_{19}	3	3	3	4	-	5	4	4	4	4	2	2	2
O_{20}	5	-	-	4	3	3	4	5	2	4	2	2	2

Stage 1. Interpolation problem. Here the following operations are the best ones: O_6 (change of existing software for improvement of picture quality); O_8 (change of software for existing telecommunication technology); and O_{12} (decreasing of losses).

Stage 2. Planning for several years. Here the following operations are the best ones: O_8 ; O_9 (change of hardware for existing telecommunication technology).

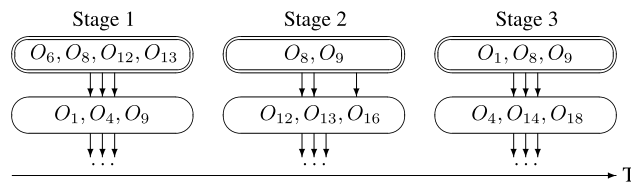


Fig. 13. The best and 'quasi-best' change operations.

Stage 3. Planning for 5–10 year. In this case, the following operations are the best ones: O_1 (extension of interface with applied systems (storage)); O_8 ; and O_9 .

At the same time, it is reasonable to examine some operations which are close to the best ones (i.e., 'quasi-best'):

Stage 1: O_1, O_4 , and O_9 .

Stage 2: O_1, O_6, O_{12} , and O_{13} .

Stage 3: O_4, O_{14} , and O_{18} .

Fig. 13 depicts the pointed out change operations. Further, it is possible to consider an additional problem:

Design a trajectory of change operations while taking into account their interconnection.

Second, numerical examples of clustering for change operations above are examined. The clustering process can be based on the following approaches: (i) engineering analysis (i.e., expert judgment); (ii) clustering based on the operations estimates (Table 7); (iii) clustering based on binary relation(s) over the operations (e.g., Table 4, Figs. 10, 11); and (iv) a hybrid approach. Here a numerical example for the first case above is considered. The compressed set of operations is: $\{O_1, O_4, O_5, O_6, O_7, O_8, O_9, O_{10}, O_{12}, O_{14}\}$. As a result, the following clusters are obtained (a basic version of the well-known agglomerative algorithm is used): cluster 1: $\{O_1, O_9\}$; cluster 2: $\{O_4, O_8, O_{14}\}$; cluster 3: $\{O_5, O_{10}, O_{12}\}$; cluster 4: $\{O_6\}$; and cluster 5: $\{O_7\}$.

Third, knapsack problem is used. Here the same compressed set of change operations is examined (as for clustering problem). The estimates upon C_{10} are used as the resource estimates (Table 7). The priorities for Stage 2 (Table 7) are used as estimates of profit (priority 1 is changed by 3 for maximization knapsack problem). On the basis of a simple algorithm (a greedy algorithm, the resource constraint equals 15), the following operations are selected: $\{O_1, O_5, O_9, O_{12}\}$.

Four, multiple choice problem is considered. Here the results of clustering above are used for our numerical example (a greedy algorithm, the resource constraint equals 15): $\{O_4, O_{10}, O_6, O_7\}$ (an operation is not selected for cluster 1).

Five, combinatorial morphological synthesis is examined. For the example of combinatorial synthesis the five operation clusters above are considered. Thus the resultant composite decisions (combination of operations) is the following: $S = A \star B \star C \star D \star E$ where A corresponds to cluster 2 and so on. Cluster 4 contains the only one candidate O_6 and cluster 5 contains the only one candidate O_7 . Thus $D = O_6, E = O_7$ and a three-component composite system is examined (Fig. 14).

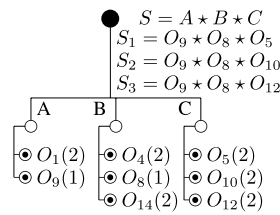


Fig. 14. Example of combinatorial synthesis (priorities are shown in parentheses).

Table 8
Compatibility

	O_4	O_8	O_{14}	O_5	O_{10}	O_{12}
O_1	1	1	1	1	1	1
O_9	1	2	1	1	1	1
O_4				2	2	2
O_8				1	1	1
O_{14}				2	1	1

Estimates of priorities are based on information from Table 7 (Stage 2). Table 8 involves compatibility estimates. It is assumed an initial compatibility estimate equals 1 and for some operation pairs the compatibility estimate is increased (on the basis of compatibility relation R^c , Table 4).

As a result, the following combinations are the best ones: $S_1 = O_9 * O_8 * O_5$, $N(S_1) = (1; 2, 1, 0)$; $S_2 = O_9 * O_8 * O_{10}$, $N(S_2) = (1; 2, 1, 0)$; $S_3 = O_9 * O_8 * O_{12}$, $N(S_3) = (1; 2, 1, 0)$. Note this example has an illustrative character. Evidently, it may be reasonable to take into account other kinds of binary relations as well.

Six, multistage design problem is considered. Here it is reasonable to use a multistage heuristic for the selection and coordination of the change operations while taking into account clusters of change operations, which are obtained on the basis of binary relations above (e.g., Figs. 11 and 12):

Phase 1. Multicriteria ranking of change operations and selection of the best and ‘quasi-best’ operations (for all time periods; Table 7, Fig. 13).

Phase 2. Extension of the operation sets on the basis of logical constraints (i.e., binary relations).

Phase 3. Generation of alternative change actions for each time stage.

Phase 4. Design of the best trajectories while taking into account interconnection of the change actions at different time stages.

Here for Phase 2 operation clusters from Figs. 11 and 12 are used. The resultant extended sets of the change operations are shown in Fig. 15.

Now it is possible to generate change actions as follows (our example has an illustrative character, in real situation special expert judgment will be required):

Stage 1 (as some two initial points):

$$A_1^1 = \{O_6, O_8, O_{12}, O_{13}, O_4, O_5, O_3\};$$

$$A_2^1 = \{O_6, O_8, O_1\}.$$

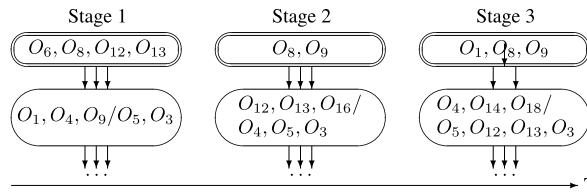


Fig. 15. Extended sets of the best and ‘quasi-best’ change operations.

Table 9
Compatibility

	A_1^2	A_2^2	A_1^3	A_2^3	A_3^3
A_1^1	3	1	3	2	0
A_2^1	2	3	2	2	1
A_1^2			3	2	0
A_2^2			3	3	3

Stage 2:

$$A_1^2 = \{O_8, O_9, O_{12}, O_{13}, O_4, O_5, O_{16}, O_3\};$$

$$A_2^2 = \{O_8, O_9\}.$$

Stage 3:

$$A_1^3 = \{O_1, O_8, O_9, O_{12}, O_{13}, O_4, O_5, O_{14}, O_{18}, O_3\};$$

$$A_2^3 = \{O_1, O_8, O_9\}; A_3^3 = \{O_1\}.$$

Fig. 16 illustrates the change actions and some ‘technological’ (change) trajectories (Da Silveira, 2002; Levin, 1998, 2006). The ‘technological’ trajectories have to contain the best change operations at each stage and very good compatibility between the selected operations at different stages. This problem corresponds to combinatorial synthesis above. In the numerical example, ordinal estimates of compatibility between change actions are considered. The estimates above are based on expert judgment (Table 9; 3 corresponds to the best level of compatibility). As a result, the following basic trajectories are obtained: $\alpha_1 = \langle A_1^1 \Rightarrow A_1^2 \Rightarrow A_1^3 \rangle$, $\alpha_2 = \langle A_2^1 \Rightarrow A_2^2 \Rightarrow A_2^3 \rangle$.

Thus it is possible to examine the obtained ‘technological’ trajectories. For example, all trajectories contain (at the second stage) change operations which are targeted to improvement of existing communication networks (O_8 and O_9). Note various optimization problems and approaches can be used for the design of the above-mentioned technological trajectories.

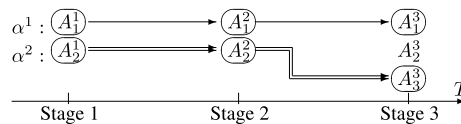


Fig. 16. Illustration for change trajectories.

6. Conclusions

We have described our structural approach to combinatorial evolution of standards in processing of multimedia information. A set of change operations has been proposed and combinatorial optimization models (including forecast) for the changes are examined. Note the analyzed standard changes are significant from the following viewpoints: (i) as ‘technological’ trajectories of the standards (i.e., standards are considered as some products); (ii) changes of the standards define some requirements to ‘technological’ trajectories of products in communication systems engineering (e.g., for algorithms, software, hardware). In the future it is reasonable to investigate the following:

- 1) other engineering systems examples (e.g., communication protocols),
- 2) usage of more complicated combinatorial models and various algorithms,
- 3) taking into account uncertainty,
- 4) usage of traditional artificial intelligence approaches (e.g., expert systems, neural networks), and
- 5) usage of combinatorial systems evolution in engineering education practice (e.g., student projects).

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Kombinatorinių sistemų evoliucija: standarto pavyzdys multimedijos informacijai

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Straipsnis yra skirtas multimedijos informacijos perdavimo standartų kombinatorinei evoliucijai. Straipsnyje pateikiama: (a) trumpas pagrindinių kombinatorinių modelių, tokių kaip daugiakriterinis rikiavimas, klasterizavimas, kombinatorinė sintezė, daugiapakopis modeliavimas, aprašymas, (b) standartų, skirtų video informacijos apdorojimui (MPEG), aprašymas ir šių standartų pokyčių sistemos struktūrinis (kombinatorinis) aprašymas, (c) sistemos pokyčio operacijų aibė (apimanti operacijų požymių ir binarių sąsajų operacijose aprašymą), (d) pokyčių sistemos kombinatoriniai modeliai, (e) pokyčių sistemos analizei skirta daugiapakopė kombinatorinė schema. Naudojamos ekspertinės žinios. Daugelis pavyzdžių iliustruoja pasiūlytas problemas, modelius ir procedūras.